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A Study on Welding Residual Stress in Elliptical Tube to Tube Sheet Joint of a Phthalic Anhydride Switch Condenser

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Abstract

Switch condenser is widely used in petroleum and chemical industries, especially in phthalic anhydride plants. The tube to tube sheet joint is an important element for the switch condenser. The welding residual stress in the tube to tube sheet joint is critical to the safety and reliability of the switch condenser. In this paper, FEM was used to predict the welding residual stress in the elliptical tube to tube sheet weld of a phthalic anhydride switch condenser. In order to validate the simulated results, a test sample with circular-shaped tube to tube sheet joint was prepared. And then the welding residual stresses in the circular tube to tube sheet weld were simulated by the FEM and studied experimentally by the X-ray diffraction method. The simulated results were compared with the test results to verify the finite element analysis. The simulated results show that the residual stress initially decreased sharply and then decreased gradually with the increase of the distance along the direction of the long axis of the elliptical weld. It is found that the maximum welding residual stress in the elliptical tube to tube sheet joint appeared at the location of 180° in the region of the elliptical weld and reached its peak value. Experimental results are in good agreement with the numerical simulation results.

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Keywords: elliptical tube; tube sheet; weld; residual stress; FEM

Nomenclature

FEM	finite element method
3D	three-dimensional
2D	two-dimensional

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1. Introduction

Switch condenser is widely used in petroleum and chemical industries, especially in phthalic anhydride plants. A switch condenser is similar to a shell-and -tube heat exchanger. During operation, the heat transfer oil travels through the tube for heat exchanger, while the phthalic anhydride is conducted through the shell. Therefore, the tube to tube sheet joint is an important element for the switch condenser. It separates the phthalic anhydride from the heat exchanger oil. If any tube-tube sheet joint degrades or fails in phthalic anhydride switch condensers, the heat transfer oil can leak out and be mixed with phthalic anhydride directly during operation. It affects not only the overall operation reducing the efficiency of phthalic anhydride production, but also poses the safety concern. The elliptical tubes are widely used in phthalic anhydride switch condensers for phthalic anhydride collection easily. The interfaces between the elliptical tube and tube sheet are particularly difficult to test due to large temperature gradients and the complicate geometry. Crack development in the elliptical tube and tube sheet welding region is a common issue. The local stress levels from the applied loading, thermal stress and residual stress contribute to the failure scenario. Thus the residual stress for the welding of tube to tube sheet is paid more and more attention [1-3].

There are substantial literatures concerning numerical investigation on welding residual stress. Xu et al. [4] used finite element method to predict the residual stresses in a tube to tube sheet weld of a heat exchanger. Kong et al. [5] developed a 3-D finite element model to investigate thermally induced stress field during hybrid laser–gas tungsten arc welding process. Barsoum et al. [6] established a 2-D welding simulation procedure and found it was suitable for residual stress predictions for incorporation in further fatigue crack growth analysis from weld defects emanating from the weld toe and the un-fused root. Moshayedi et al. [7] combined numerical simulation with experiment to investigate the welding residual stresses.

Although there are many reports regarding the numerical investigation on welding residual stress, there are few reports concerning the residual stress in elliptical tube to tube sheet joint. In this study, FEM was used to predict the welding residual stress in the elliptical tube to tube sheet weld of a phthalic anhydride switch condenser. In order to validate the simulated results, a test sample with circular-shaped tube to tube sheet joint was prepared. And then the welding residual stresses in the circular tube to tube sheet weld were simulated by the FEM and studied experimentally by the X-ray diffraction method.

2. Finite element analysis of the elliptical tube to tube sheet joint

In order to study the welding residual stress in the elliptical tube to tube sheet weld of a phthalic anhydride switch condenser, FEM was used. A 3-D sequential coupling thermal-structural analysis model was established to calculate the welding temperature and residual stress using the commercial code ANSYS. Firstly, the thermal analysis was conducted to simulate the welding temperature history. Secondly, the temperature results were applied incrementally to the structural model to calculate the welding residual stress. For the finite element analysis, birth and death element technique was used to move the load of welding heat source and to simplify the solution process. In addition, the thermal-structure couple function was used in ANSYS code for the analysis in this work

2.1. Geometrical parameters and meshing

The geometry and dimensions of the elliptical tube to tube sheet joint are shown in Fig. 1. For the convenience of this calculation, an elliptical-shaped tube sheet was modeling in this simulation. The thicknesses of the tube and the tube sheet are 2.5 mm and 12mm, respectively. The dimensions of the elliptical tube sheet are 90mm in the long axis and 45mm in the short axis. The dimensions of the elliptical tube are 44mm in the long axis and 16mm in the short axis. A 3-D model was established based on the actual structure and is shown in Fig. 2. The finite element model consisted of 14186 elements and 19434 nodes after meshing. The indirect method was used in the simulation. Based on the temperature field results, welding residual stresses were calculated by changing thermal elements. The element types are SOLID70 and SOLID 90 for the thermal analysis and SOLID 45 and SOLID 95 for the structural analysis.

2.2. Material properties

The tube sheet was made of low alloy steel Q345R in a Chinese grade, which is the same as the material of weld metal. The material of the tube is 20 steel in a Chinese grade. For thermal and mechanical analysis, thermo-physical and mechanical properties [8] of the materials at various temperatures are listed in Table1.

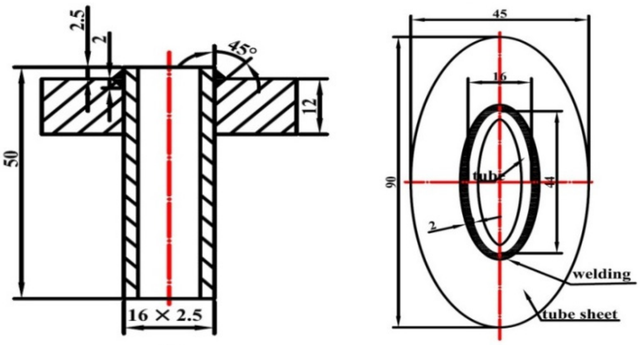

Fig. 1. Geometry and dimensions of the tube and tube sheet weld.

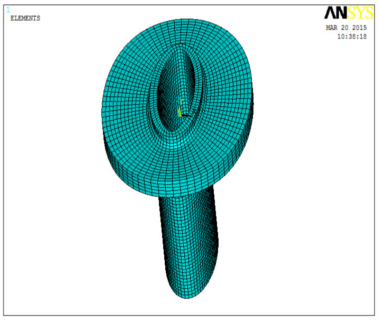

Fig. 2. Model for finite element analysis.

Table 1. Material properties for Q345R and 20 steel.

Material	Temperature (℃)	Young's Modulus (GPa)	Yield strength (GPa)	Density (kg/m3)	Poisso's ratio	Thermal Expansion (W/m℃)	Specific conductivity (J/kg·℃)
20#	25	193	0.245	7850	0.3	50	460
20#	500	150	0.2	7850	0.3	50	460
20#	1000	70	0.1	7850	0.3	50	460
20#	1500	10	0.014	7850	0.3	50	460
20#	2000	1	0.0014	7850	0.3	50	460
Q345R	25	206	0.345	7850	0.3	45	502
Q345R	500	170	0.3	7850	0.3	45	502
Q345R	1000	90	0.15	7850	0.3	45	502
Q345R	1500	20	0.02	7850	0.3	45	502
Q345R	2000	1	0.002	7850	0.3	45	502

2.3. Thermal analysis

The formation of welding residual stress was due to the uneven temperatures produced by the moving of welding heat source [9]. The heat of the welding arc was modeled by a surface heat source with a Gaussian distribution in this study. The Gaussian distribution of heat flux is shown in Fig. 3. In order to further analyze the welding residual stress, three paths, namely P1、P2 and P3, are defined as shown in Fig. 4. Path P1 is along the center of weld from the beginning of the welding (i.e. 0° in Fig. 4) to the end of the welding (i.e. 360°). Path P2 is along the direction of long-axis of the elliptical tube sheet from the center of the weld to the outside of the tube sheet. Path P3 is along the direction of short- axis of the elliptical tube sheet from the center of the weld to the outside of the tube sheet.

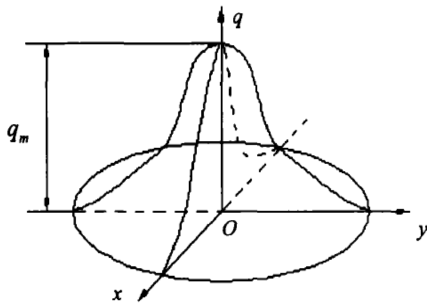

Fig. 3. Heat-flow density of Gaussian distribution.

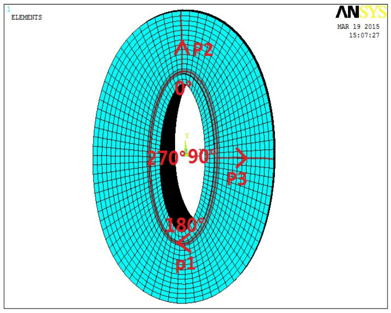

Fig. 4. Different paths in the tube-tube sheet joint.

2.4. Structural analysis

As mentioned above, the residual stress is calculated by using the temperature results obtained from the thermal analysis as input data. The material properties related to the residual stress are Young's model, yield strength, Poisson's ratio and coefficient of thermal expansion. During the structural analysis, NLGEOM was set to on. Element birth and death technology was also used for the stress analysis. During the welding, there is no stress in the molten pool. Therefore, the technology can "kill" the weld metal element [10].

3. Verification of the finite element analysis

In order to verify the results of numerical simulation of the elliptical tube to tube sheet weld, a test sample with circular-shaped tube to tube sheet joint was prepared as shown in Fig. 5. The dimensions of the tube sheet are 60mm in length, 60mm in width and 12mm in thickness. The dimensions of the tube are 28mm in the outside diameter, 23mm in the inside diameter and 50mm in the length. The geometry and dimensions of the weld cross-section for the welding are the same as those shown in Fig. 1. The tube sheet was made of low alloy steel Q345R in a Chinese grade, which is the same as the material of weld metal. The material of the tube is 20 steel. The welding method and welding parameters for the circular tube to tube sheet joint are the same as those used for the elliptical tube to tube sheet joint.

Based on the test sample structure, a 3-D model was built and is shown in Fig. 6. The element types for the thermal and structural analysis are as the same as those in the model shown in Fig. 2. The meshing, boundary conditions and applied loads are also similar to those in the model shown in Fig. 2. For the thermal and mechanical analysis, thermo-physical and mechanical properties of the materials at various temperatures are the same as those listed in Table1. The finite element analysis was conducted for the circular tube to tube sheet joint. The simulated results are shown in Fig. 7.

In order to verify the finite element analysis, the X-ray diffraction method was employed to study the welding residual stress. Eight test points along the center of the weld to the outside of tube sheet were chosen for the test as shown in Fig. 5.The distance between two points is 1.5mm in this work. The experimental results are also shown in

Fig. 7. It can be seen from Fig. 7 that the simulated results are in agreement with the experimental results. It indicates that the finite element program developed here can be used for residual stress analysis in the elliptical tube to tube sheet joint in this study.

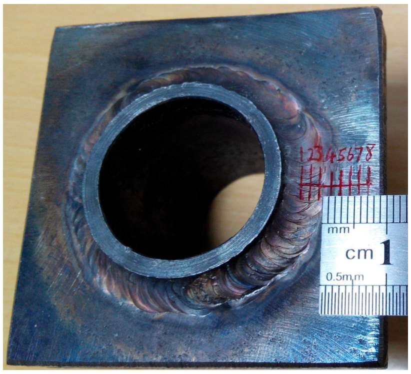

Fig. 5. The picture of the test sample.

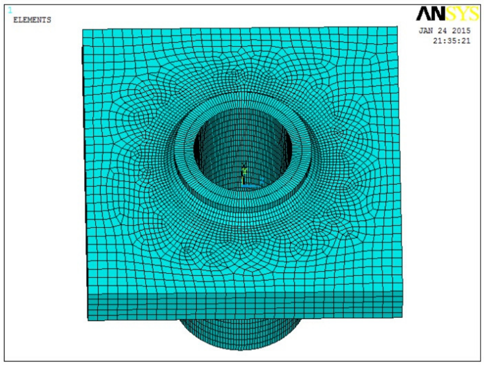

Fig. 6. The finite element model.

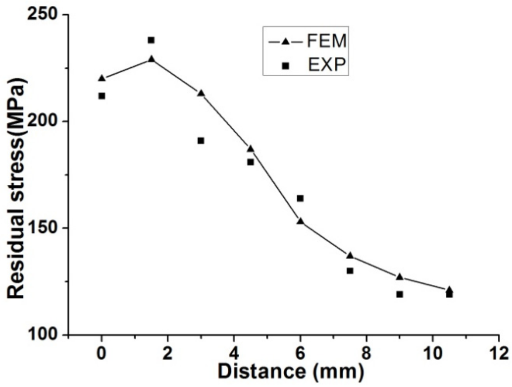

Fig. 7. Comparison of residual stress results between by FEM and by experimental measurement.

4. Results and discussion

Figures 8(a), (b), (c) and (d) show the simulated results of Von Mises stresses at the welding times of 1s, 7s, 11s and 15s, respectively. It can be seen from Fig. 8(a) to Fig. 8(d) that there were no stresses at the instantaneous location of the heat source during welding, while the stresses appeared away from the welding heat source.

The simulated results of the welding residual stress in the elliptical tube to tube sheet joint of the phthalic anhydride switch condenser are shown in Fig. 9. From Fig. 9, it can be observed that the Mises stresses in the region of the elliptical weld were larger than those in other areas, and the Mises stress decreased with the increase of distance away from the weld. It is found from Fig. 9 that the maximum residual stress for welding appeared in the weld along the direction of long axis of the elliptical weld.

Figure. 10 shows the residual stresses along the reference path P1. It can be seen from Fig. 10 that the locations of 0°, 180° and 360° in the region of the elliptical weld had large residual stresses compared with the locations of 90° and 270° in the region of the elliptical weld. It is found from Fig. 10 that the peak stress at location of 180° was not equal to that at location of 0° or 360°. This could be due to heat treatment as the heat source moved to the beginning of the weld again. The maximum residual stress appeared at the location of 180° in the region of the elliptical weld and reached its peak value at 407MPa.

Figure 11 indicates the residual stresses along the reference paths P2 and P3. It can be observed that the residual stress decreased gradually with the increase of the distance along the path P3 from the elliptical weld to tube sheet. However, the residual stress decreased initially sharply with the increase of the distance along the path P2, and then the residual stress decreased gradually with the increase of the distance when the distance was larger than 2.5 mm.

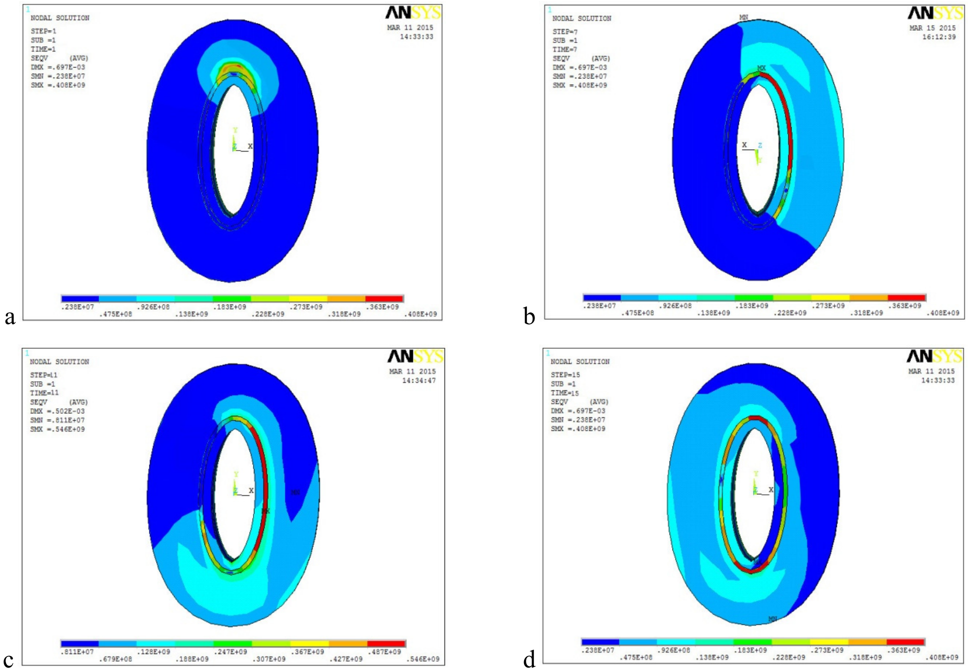

Fig. 8. The Von Mises stress distribution at (a) 1s, (b) 7s, (c) 11s and (d) 15s.

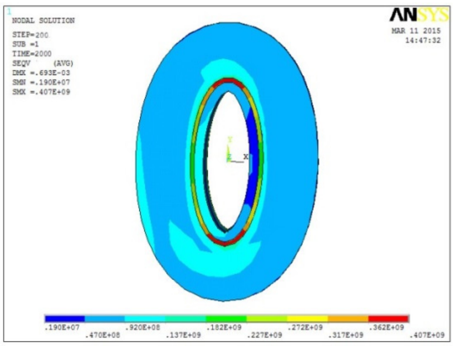

Fig. 9. Residual stress distribution after welding.

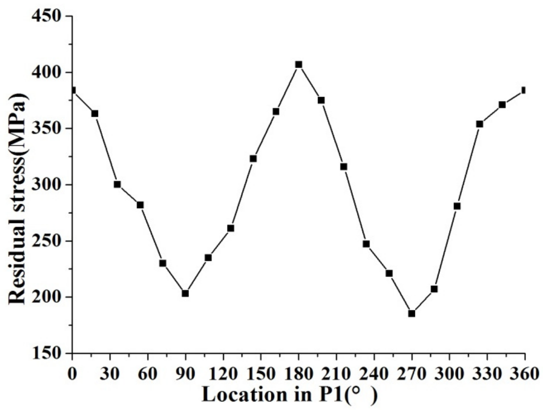

Fig. 10. The residual stresses along the path P1.

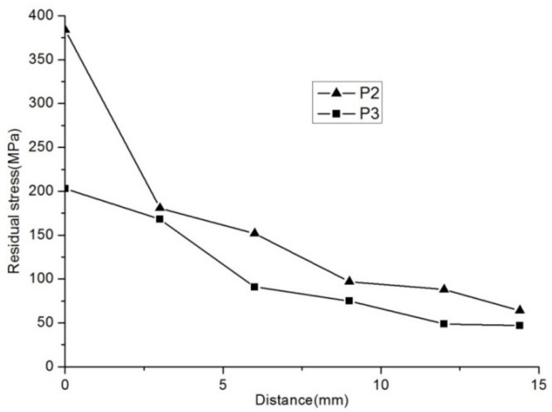

Fig. 11. The residual stresses along paths P2 and P3.

5. Conclusions

The welding residual stress in the elliptical tube to tube sheet joint of the phthalic anhydride switch condenser was investigated using finite element method. A test sample with circular-shaped tube to tube sheet joint was also studied both numerically and experimentally to verify the finite element analysis. The following conclusions can be made.

1) The simulated results show that the welding residual stresses in the region of the elliptical weld were larger than those in other areas, and the residual stresses decreased with the increase of distance away from the weld. The maximum welding residual stress appeared in the weld along the direction of long axis of the elliptical weld.

2) The peak residual stress at location of 180° was not equal to that at location of 0° or 360° in the region of the elliptical weld. The maximum peak residual stress appeared at the location of 180° in the region of the elliptical weld and reached its peak value at 407MPa in this work.

3) The residual stress decreased initially sharply with the increase of the distance along the path P2, and then the residual stress decreased gradually with the increase of the distance when the distance was larger than 2.5 mm.

4) Experimental results are in good agreement with the numerical simulation results. The results in this work could be useful to the optimal design of the tube and tube sheet joint of phthalic anhydride switch condensers.

Acknowledgements

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